7. Technology Complexity and Mass Minimization Approaches

In this chapter an approach is presented that for a given G/T at the Earth terminal, provides the satellite EIRP required for a given data rate in terms of minimum technology risk design, as defined in section 7.1.1. The approach starts from an initial design made according to the criterion of minimum total mass of the antenna and RF power subsystems. Using definitions of technology risk, or complexity, for both subsystems, the design is refined such that the minimum technology complexity is provided at the lowest possible total mass.

The approach is quite general. Results are presented for transmission of three data rates at the maximum Mars-Earth range (2.67 AU, the furthest point from Earth for the relay satellite): 1 Gbps, 500 Mbps, and 100 Mbps. All designs are for a Ka-band downlink with 90 percent link availability, a bandwidth of 500 MHz, and dual polarization when required. The link budgets upon which these results are based are given in appendix 4A.

In addition, the CEV-Earth link design is given for a CEV in transit to and from Mars. These results are then tied to the Mars relay results to determine if there is an efficient way to utilize the same ground array resources to simultaneously support both an in-transit CEV and explorers and instruments at Mars.

7.1 Design Approach for Maximum Range

In designing the return link from 2.67 AU to Earth, there is a three-dimensional physical element trade space to consider: net G/T of the ground antenna system; satellite RF power; and size of the spacecraft antenna. In this trade space the ground antenna system is taken to be the future DSN array described in chapter 3. The design approach for this link is to first determine, for a given data rate and ground G/T, the set of satellite antenna and RF power options that provide the required EIRP; from among these options, one is selected that minimizes technical risk and achieves the smallest possible satellite payload mass (antenna plus RF power system), according to an algorithm developed in the chapter.

7.1.1 Technology Risk

In this section we define technical risk in terms of a complexity factor and show how this factor is applied to the spacecraft antenna and power potential capabilities. The complexity factor was introduced by Mankins (ref. 7–1) to complement the TRLs metric. Complexity factor is a measure of expected difficulty in the maturation of a technology. Whereas TRL assesses the maturity of a particular technology, the complexity factor attempts to quantify the "Research and Development Degree of Difficulty (R&D3)" associated with achieving a technical objective.

Mankins defines a set of criterion to enable one to determine the numerical complexity factor. Table 7–1 applies Mankins' definitions to large deployable antenna system technology. Note that this assessment is not restricted to just deployable reflector antennas, but takes the broader view of a functional antenna system, including the potential need for fine-beam pointing. In this view, overall complexity is driven not by reflector technology itself, but by the potential for fine-beam pointing. Even for comparatively small reflectors, uncertainty and risk associated with beam-pointing technologies (e.g., thermal distortion of reflector, deployment accuracy and dynamics of reflector and boom, ADCS control accuracy, etc.) lead to a finite probability that active fine-beam pointing may be needed.

TABLE 7–1.—EXPLANATION OF COMPLEXITY FACTOR FOR ANTENNA SYSTEMS

Ka-band reflector diameter, m	R&D complexity	Justification
<6	1	Probability of success in "normal" R&D effort 99%. A very low degree of difficulty is anticipated in solving technical problems with mesh or flat membrane; taco shell stowage may be adequate. Fine-beam pointing control not needed due to insensitivity of feed positioning and thermal. Similar systems space proven at lower frequencies. A focused, short-duration, development effort on mesh reflectors (longer for inflatables) should assure a high probability of success in development of a deployable reflector.
6 to 9	2	Probability of success in "normal" R&D effort 90%. A moderate degree of difficulty anticipated to solve technical problems with mesh reflectivity, flat membrane, or inflatable technology. One approach will probably be sufficient; however, differing technologies offer quite a range of stowage options that may be needed to achieve success in later systems applications. Very low probability that fine-beam-pointing control is needed due to insensitivity of feed positioning and thermal. Mesh systems space proven at lower frequencies.
9 to 14	3	Probability of success in "normal" R&D effort 80%. A higher degree of difficulty anticipated to solve technical problems with mesh reflectivity, flat membrane, or inflatable technology due to larger deployed area. Two approaches will probably be needed to offer useful range of stowage options for future systems applications. Moderate probability that fine-beam-pointing control is needed due to insensitivity of feed positioning and thermal. Preliminary R&D on fine-beam-pointing systems needed. Mesh systems space proven at lower frequencies.
14 to 24	4	Probability of success in "normal" R&D effort 50%. A very high degree of difficulty anticipated to solve technical problems with mesh reflectivity, flat membrane, or inflatable technology due to large deployed area. High probability (~50%) that fine-beam-pointing control is needed due to insensitivity of feed positioning and thermal. Multiple approaches will be needed to offer useful range of stowage options and fine-beam-pointing option for future systems applications. Focused R&D on fine-beam-point systems needed. Mesh systems space proven at lower frequencies.
>24	5	Probability of success in "normal" R&D effort 10 to 20%. A very high degree of difficulty anticipated to solve technical problems with mesh reflectivity, flat membrane, or inflatable technology due to very large deployed area. Very accurate fine-beam-pointing control required due to insensitivity of feed positioning, deployment tolerances, and thermal. The degree of difficulty achieving fundamental breakthrough in fine-beam-pointing control and possibly in positioning accuracy may be needed to achieve a practical, cost-effective system. Basic research in key areas related to antenna beam-pointing system design and beam-pointing control needed before feasible system concepts can be refined.

Mankins' complexity factors are utilized to assess complexity levels for RF power in a similar manner in table 7–2. Parallel to the antenna findings, the dominant constraint for generating high power is not the power level itself, but rather the ability to control the heat dissipated in the (less than 100 percent efficient) generation of the power.

TABLE 7–2.—EXPLANATION OF COMPLEXITY FACTOR FOR RF POWER SYSTEMS

Ka-band RF power, W	R&D complexity	Justification
≤250	1	Probability of success in "normal" R&D effort 99%. A very low degree of difficulty is anticipated in solving technical problems with a TWTA. A 180-W transmitter is being space qualified today. The same design has been shown to operate stably up over 250 W.
>250 to 500	2	Probability of success in "normal" R&D effort 90%. A moderate degree of difficulty anticipated to solve technical problems with TWTAs. Waveguide power combining of multiple tubes has been demonstrated at Ka-band. The heat loads are not significant.
>500 to 1000	3	Probability of success in "normal" R&D effort 80%. A higher degree of difficulty anticipated to solve technical problems with TWTAs. Handling the heat loads onto the waveguides becomes an engineering challenge. Waveguides must remain short.
>1000 to 2500	4	Probability of success in "normal" R&D effort 50%. A very high degree of difficulty anticipated to solve technical problems with TWTAs. Handling the heat loads onto the waveguides becomes an engineering challenge. Waveguides must remain short.
>2500	5	Probability of success in "normal" R&D effort 10 to 20%. A very high degree of difficulty anticipated to solve technical problems with TWTAs. If heating could be handled, waveguide power combining fails due to multipaction. Spatial power combining of multiple feeds could be used at these higher powers but the mechanical systems to operate are probably at least difficult. It is worth noting that transmitters of 100 kW are used in the DSN. They are water cooled, not space qualified, and probably are not helical TWTs.

7.1.2 The Global Minimum Mass Design Solution

To optimize the spacecraft RF mass (antenna plus power subsystem) without regard to technology complexity, one calculates the EIRP requirement to close the link, and then determine the set of (antenna size and RF power) pairs that will achieve that EIRP. For fixed EIRP, the antenna diameter (d) and the RF power (P) must be related according to

$$P \cdot d^2 = \text{constant} \tag{7.1}$$

Knowing how the antenna and power system masses depend on diameter and power, it is possible to compute the summed mass and minimize over all $\{d, P\}$ pairs conforming to the constraint (eq. (7.1)). We take antenna mass (m_a) to be proportional to the aperture area (diameter squared) and power system mass (m_p) proportional to output power.[1] Equation (7.2) then shows that the spacecraft mass (m_{a+p}) is minimized when the antenna diameter and RF power are chosen such that the mass of the antenna equals the power mass—see appendix 4C for derivation and definition of the link parameters that appear in the result.

[1]One might expect a model that takes mass as proportional to d^3 (volume), but the primary antenna types considered are mesh deployables and inflatables, which do not necessarily have proportional growth in thickness as the diameter expands.

$$m_{a+p} = 2m_a = 2m_p = \lambda \sqrt{\frac{EIRPd_a d_p}{L_t \eta_{ap} \pi}} \tag{7.2}$$

This solution for minimum mass of the combined antenna and power systems provides a single-point design. If one is willing to tolerate a combined mass slightly greater than the theoretical minimum, the design space opens up rather quickly, making room for designs that may be more technologically feasible without much sacrifice in the mass goal.

7.1.3 Near-Optimum Total Mass Solutions

Let $\hat{m}_T$ denote the globally optimum total mass and $\hat{m}$ be the optimum component mass, where $2\hat{m} = \hat{m}_T$. Suppose solutions having total mass as great as $\alpha\,\hat{m}_T$ can be tolerated, for some scale factor $\alpha > 1$. It is shown (see appendix 7A) that the components m_a and m_p must then satisfy

$$m_- = \left[\alpha - \sqrt{\alpha^2 - 1}\right]\hat{m},\ m_+ = \left[\alpha + \sqrt{\alpha^2 - 1}\right]\hat{m}, \tag{7.3}$$

where m_- denotes the smaller of m_a and m_p, and m_+ denotes the larger. That is, as total mass increases above optimum, one of the components will increase in mass as the other decreases.

Figure 7–1 shows this range of variation versus α; in the figure, α is represented as a percentage increase in total mass, mathematically equivalent to $100(\alpha - 1)$ percent. The red curve indicates the mass of whichever subsystem has been increased above optimum, that is, m_+; the blue curve denotes the mass of the other (m_-). For even a modest mass increase of 10 percent ($\alpha = 1.1$), the case illustrated in figure 7–1, the component mass values lie as far as 56 percent above or 36 percent below their optimum values. For larger mass increases the range of potential mass variation in the components is quite wide.

7.2 Optimum Mass Subject to Minimization of Technology Complexity

7.2.1 The Mass-Technology Trade Space and Technical Approach

The technology risk factors of table 7–3 and the mass equations (7.2) and (7.3), lead to the trade space shown in figure 7–2. The figure shows the technology risk level of a given antenna/power pair according to the five-level color coding established in table 7–3. (The blue area in the figure corresponds to the blue font in the table.) The color at each point in the space corresponds to the greater of the antenna and power complexity levels. In addition, there are curves of RF power versus antenna size corresponding to various values of constant EIRP.

As figure 7–2 illustrates, the paired selection of antenna and power systems can vary significantly for a given EIRP, resulting in designs where either or both subsystems have a high technology risk. There is no a priori assurance that the mass-optimal design will lie in a low-risk sector. Since constant EIRP requires the power to vary inversely with the square of the antenna diameter, an increase in the mass one of the two systems causes a mass decrease in the other. Moving the design along a constant EIRP curve will sometimes result in a solution that is slightly more massive than the optimum, yet significantly lower in overall risk.

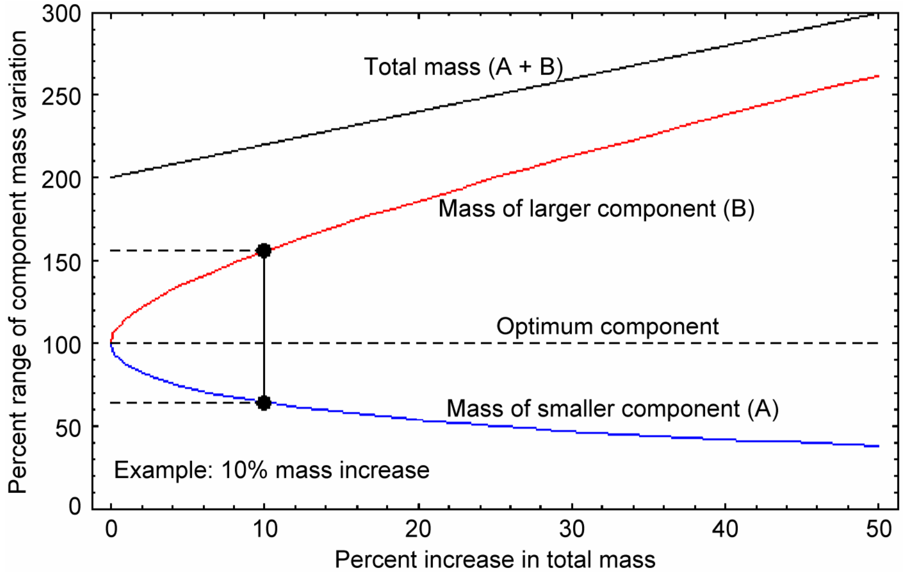

Figure 7–1.—Range of variation in mass relative to optimum versus percentage increase in total mass.

TABLE 7–3.—ANTENNA AND RF POWER SUBSYSTEM TECHNOLOGY COMPLEXITY RATINGS

Complexity Level	Complexity Definition	Range of Antenna Diameter (m)	Range of RF Power (W)
1	Low	< 6	< 250
2	Moderate	6–9	250–500
3	Moderate to Difficult	9–14	500–1000
4	Difficult	14–24	1000–2500
5	Very Difficult	> 24	> 2500

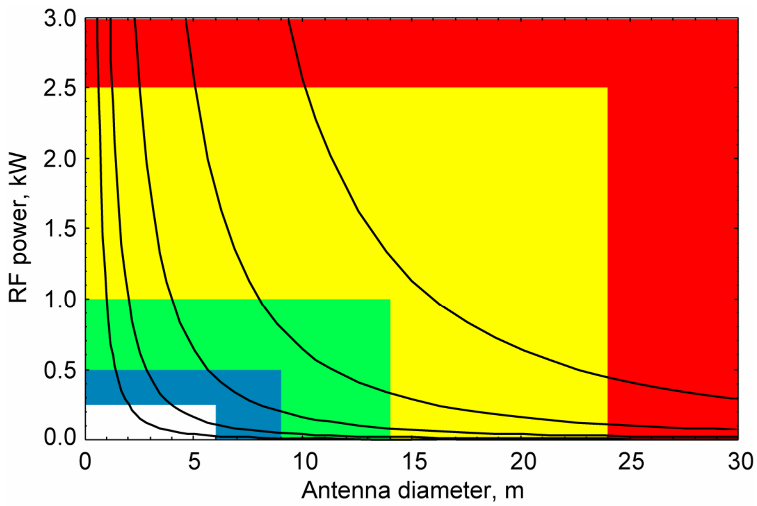

Figure 7–2.—Relationship of antenna and power complexity levels for constant values of EIRP. The color regions depict technology complexity as the greater of the two component complexities.

The lower the mass, the lower the complexity factor for a given subsystem. As an example, if the EIRP corresponds to the lowest value—leftmost curve—among those shown in figure 7–2, then selecting an RF power value of, for example, <100 W and the paired antenna of approximately 2 m would provide the least risk and the lowest mass. That is, selecting an RF power value of 3 kW reduces the antenna diameter requirement to less than a meter for the same EIRP, but increases the power amplifier technology risk to its highest level and increases the EIRP mass.

The approach taken in this paper is to first determine the power and antenna systems for minimum mass. Technical risk factors consistent with table 7–3 are then applied to each system. If the component risk levels are unequal, the higher of the two levels is associated with the risk in developing the required EIRP. In such cases the minimum mass will be increased if the EIRP complexity level can be reduced.

7.3 Results and Comparisons for the 2.67 AU Mars-Earth Link

The results that follow show the variation in satellite antenna and power requirements for the Mars-to-Earth link as a function of Earth G/T (as represented by the number of 12-m receive antennas used in the DSN array), data rate, and antenna mass density.

7.3.1 Sensitivity of Complexity to Paired Antenna-Power Selection

Table 7–4 investigates for several designs whether global mass optimization results in a minimum technical complexity. Cases examined encompass data rates 1, 0.5, and 0.1 Gbps, and antenna ground arrays that vary from 3 to 180 antennas. Where complexity reduction is possible, a second design is given.

TABLE 7–4.—ANTENNA-POWER SELECTION SENSITIVITY TO COMPLEXITY

Antenna Mass Density: 2 kg/m^2

External Constraints		Minimum Mass Design						Minimum Technical Risk Design						
Number of 12-m Array Antennas	Data Rate (Gbps)	S/C Antenna Diameter (m) and Complexity		Output Power (kW) and Complexity		Total Mass (kg) and Complexity		S/C Antenna Diameter (m) and Complexity		Output Power (kW) and Complexity		Delta Mass (kg)	Total Mass (kg) and Complexity	
180	1.0	5.0	1	0.82	3	79.5	3	6.5	2	0.49	2	0.0	90.2	2
90	1.0	6.3	2	1.03	3	112.9	3	6.3	2	1.03	3	0.0	112.9	3
45	1.0	7.4	2	1.49	4	174.0	4	9.0	2	1.01	3	23.0	186.7	3
24	1.0	8.8	2	2.03	4	238.0	4	12.1	3	0.83	3	0.0	279.0	3
12	1.0	10.3	3	2.89	5	336.6	5	11.1	3	2.49	4	14.0	339.9	4
180	0.5	4.3	1	0.56	3	57.7	3	4.6	1	0.49	2	0.0	58.3	2
90	0.5	5.1	1	0.79	3	81.5	3	6.5	2	0.49	2	0.0	91.4	2
45	0.5	6.0	1	1.14	4	115.2	4	6.5	2	0.97	3	2.6	116.3	3
24	0.5	7.1	2	1.53	4	157.8	4	8.8	2	1.00	3	21.0	172.8	3
12	0.5	8.4	2	2.18	4	223.0	4	12.4	3	0.10	3	0.0	293.0	3
180	0.1	2.7	1	0.28	2	23.1	2	3.3	1	0.19	1	0.0	24.9	1
90	0.1	3.4	1	0.36	2	36.4	2	4.6	1	0.19	1	0.0	43.2	1
45	0.1	3.8	1	0.57	3	46.2	3	4.1	1	0.49	2	0.4	46.6	2
24	0.1	4.5	1	0.76	3	63.3	3	5.6	1	0.49	2	6.0	69.6	2
12	0.1	5.6	1	0.98	3	99.6	3	5.6	1	0.98	3	0.4	99.6	3
6	0.1	6.7	2	1.36	4	140.7	4	7.9	2	0.98	3	12.3	148.5	3
3	0.1	8.2	2	1.82	4	212.6	4	11.1	3	0.99	3	0.0	249.5	3

In evaluating these results the following observations can be made:

1. At 1 Gbps, technology complexity can be decreased in all but one case, namely, when the antenna array size is 90. For all cases in which the complexity factor is decreased there is a corresponding increase in total mass. For a 45-antenna array, the satellite antenna size increases from 7.4 to 9.0 m, while the power is reduced from 1.5 to 1.0 kW. Antenna complexity is unchanged but power complexity drops from 4 to 3. To achieve this risk reduction the mass increases by only 7.3 percent. Likewise, when the Earth array has 24 antennas, adding 17.2 percent to the mass reduces power from 2.0 to 0.8 kW, while reducing power complexity to level 3. This is achieved by increasing antenna size from 8.8 to 12.1 m—an increase in antenna complexity from 2 to 3. Thus the overall complexity level drops from level 4 to 3 (power complexity being the design limitation).
2. In several cases the risk-optimum solution is also mass-optimum, even though the complexity level for the antenna is less than the power complexity level—and hence, the overall complexity level. In these cases power complexity cannot be reduced without increasing antenna complexity.
3. In all cases, and under either optimization criterion, where there is a difference in the complexity level between the antenna system and the power system, the constraining system (higher complexity level) is the power system.

7.3.2 Results as a Function of Data Rate

TABLE 7–5.—PERCENT MASS REDUCTION AS A FUNCTION OF DATA RATE REDUCTION (ANTENNA MASS DENSITY 2 kg/m^2)

Data Rate	1.0 Gbps		0.5 Gbps		0.1 Gbps		0.5 Gbps	0.1 Gbps
Number of 12-m Ground Antennas	Total Mass (kg) and Complexity		Total Mass (kg) and Complexity		Total Mass (kg) and Complexity		Percent Mass Reduction from 1 Gbps	
180	90.2	2	58.3	2	24.9	1	35.4	72.4
90	113.8	3	91.4	2	43.2	1	19.7	62.0
45	186.7	3	116.3	2	46.6	2	37.7	75.0
24	279.0	3	172.8	2	69.6	2	38.1	75.1
12	339.9	4	293.0	3	99.6	3	13.8	70.7
6	533.2	4	296.7	3	148.5	3	44.4	72.1
3	828.6	4	515.0	3	249.5	3	37.8	69.9

Table 7–5 presents results as a function of data rate. In evaluating these results the following observations can be made:

1. A level-2 complexity factor can be achieved for 1 Gbps transmissions with 180 array elements, but rises to 3 for 1 Gbps and antenna arrays having 24 to 90 elements. The mass of satellite RF payload, which can be as low as 90.2 kg for a ground array of 180, approximately doubles for a reduction of array size (by a factor of 4) to 45. This is

explained by equation (7.2), which shows that optimum mass is proportional to the square root of EIRP. Accepting level-4 complexity permits a reduction of the array size to 12 or 3. The final masses in these three cases are 340, 533, and 829 kg, respectively.

2. At 0.5 Gbps, complexity level 2 can be achieved with arrays of 180 or 90 antennas on the ground, with respective masses of 59 and 91 kg. For the EIRP design for all listed smaller ground arrays the complexity level is 3. In comparing results for 1 Gbps with that of 500 Mbps, it can be seen that approximately the same mass is achieved with half the number of receive antennas. In addition, the complexity level for a given ground array is either the same or reduced by one as the data rate is halved.
3. A 24-antenna array can support 100 Mbps at level-2 technical risk. Increasing risk level to 3 permits reduction of the array to 3 to 12 antennas.
4. As the antenna array is reduced in size by a factor of 7.5 from 180 to 24 in support of 100 Mbps, the mass increases by a factor of 2.74 from 25 kg (180 antennas) to 70 kg (24 antennas). The proportionality of mass to the inverse square root of the number of antennas is evident in this case. Although this proportionality exists in most cases, there are exceptions that occur when mass increases greater than 10 percent are required to reduce the complexity level. Thus, for example, an array of 180 is a factor 60 greater than an array of 3, but the mass difference is a factor of 10, which is greater than the optimum 7.74. In this case a mass increase of 17.4 percent from the minimum was needed to reduce the complexity factor (see table 7–4).
5. For a fixed-size Earth array, a reduction in data rate from 1 Gbps to 500 Mbps enables the transmitter EIRP mass to be reduced by anywhere from 13.8 to 44.4 percent. A 90-percent reduction in data rate—1 Gbps to 100 Mbps—yields mass reductions between 62.0 and 75.1 percent.
6. Note that today's technology will allow the transmission of 100 Mbps with an array of 90 antennas on the ground.

7.3.3 Results as a Function of Antenna Mass Density

All results shown thus far assume an antenna mass density of 2 kg/m^2. As discussed in chapter 5, the achieved density potentially may be reduced by a factor of 2.

Table 7–6 contains results for both antenna density factors. As shown in the table, the complexity levels in several cases can be reduced by one via the reduction in mass density from 1 to 2 kg/m^2. In addition, density reduction can lead to EIRP total mass reductions by a factor of $\approx\sqrt{2}$, equivalent to reducing the array size by half. Thus, for example, an array requirement of 180 antennas can be reduced to 90 for any given data rate for approximately the same mass.

TABLE 7–6.—TOTAL MASS RESULTS AS A FUNCTION OF ANTENNA MASS DENSITY

		Antenna Mass Density 2 kg/m²		Antenna Mass Density 1 kg/m²	
Number of 12-m Ground Antennas	Data Rate Gbps	Total Mass (kg) and Complexity		Total Mass (kg) and Complexity	
180	1	90.2	2	58.2	2
90	1	113.8	3	89.7	2
45	1	186.7	3	115.6	3
24	1	279.0	3	172.2	4
12	1	339.9	4	222.7	4
180	0.5	58.3	2	40.8	2
90	0.5	91.4	2	58.2	2
45	0.5	116.3	3	90.5	2
24	0.5	172.8	3	112.6	3
12	0.5	293.0	3	172.2	3
180	0.1	24.9	1	18.2	1
90	0.1	43.2	1	24.7	1
45	0.1	46.6	2	32.6	2
24	0.1	69.6	2	45.0	2
12	0.1	99.6	3	74.3	2
6	0.1	148.5	3	89.7	3
3	0.1	249.5	3	155.2	3

In comparing the impact of the two antenna mass density functions on the antenna size and the power requirement, as shown in table 7–7 we observe the following:

1. In reducing the antenna mass density for 1 Gbps transmission, the antenna remains essentially the same size in all cases, but for an array of 90 elements, where it must increase from 6.5 to 9.0 m to reduce complexity level. The power also remains essentially the same for all cases, but for the array of 90 elements it can decrease and result in a lower complexity level, since the associated antenna does not cross a complexity boundary.
2. For 0.5 Gbps, the 1-Gbps summary applies, except for one case of complexity decrease, a ground array of 45 antennas. The characterization of the antenna and power changes is comparable to the 90-antenna, 1-Gbps case.
3. In reducing the antenna mass density for 1-Gbps transmission, the antenna and power remain essentially the same size in all cases, but for an array of 12 elements, where there is an antenna increase from 5.6 to 7.9 m and a power decrease from almost a kilowatt to 492 W, the complexity level decreases from 3 to 2.

TABLE 7–7.—ANTENNA DIAMETER AND TRANSMIT POWER RESULTS AS A FUNCTION OF ANTENNA MASS DENSITY

		Antenna Mass Density			
		2 kg/m^2		1 kg/m^2	
Number of 12-m Ground Antennas	Data Rate Gbps	Antenna (m)	Power (W)	Antenna (m)	Power (W)
180	1	6.5	487	6.5	487
90	1	6.5	971	9.0	506
45	1	9.0	1010	9.0	1010
24	1	12.1	832	12.4	1000
12	1	11.1	2485	11.9	2167
180	0.5	4.6	487	5.1	396
90	0.5	6.5	487	6.5	487
45	0.5	6.5	971	9.0	506
24	0.5	8.8	995	8.8	992
12	0.5	12.4	1000	12.4	1000
180	0.1	3.3	189	3.4	178
90	0.1	4.6	194	4.6	194
45	0.1	4.1	487	4.6	387
24	0.1	5.6	490	5.6	490
12	0.1	5.6	978	7.9	492
6	0.1	7.9	981	7.9	981
3	0.1	11.1	991	11.1	991

7.3.4 CEV Requirements and Their Potential Impact on the Mars-Earth Link Design

The scenario in section 2.2 states a requirement to support the CEV throughout two states: Earth-Mars transit (State 1) and Mars orbit (State 2). In State 1 the ground supports CEV with at least 1 Mbps via a direct link to Earth. Once the CEV achieves a Mars orbit it can be supported via the Mars relay network and is able to transmit tens of Mbps to Earth (State 2).

In this section we calculate the ground G/T and CEV antenna and power requirements for a 1-Mbps link at the worst-case distance, 2.67 AU. Clearly much greater data rates could be achieved through most of the voyage to Mars if the ground and CEV resources are sized for this furthest path. At a distance of half maximum range, there is another 6 dB of link margin available, and the data rate can increase by a factor of 4.

The percentage of time that the data rate can be increased by X dB can be inferred from figure 3–7, which illustrates the benefit of decreasing the distance by showing what fraction of time a given dB power savings can be achieved at a fixed data rate. One can reinterpret the figure as a plot of the percentage of time a given dB data rate increase is possible simply by changing the sign of the dB variable.

It is assumed in this section that the CEV observes the scenario constraints of 1-m antenna and 100 W. Both these values are obtained at level-1 complexity. As stated in section 2.2, the size of the antenna is constrained to 1 m since it is assumed that the antenna will have to be gimbaled to support both the CEV-to-Earth and the CEV-to-Mars-relay link connectivities at different times. Also, a larger antenna might cause visual blockage problems for the CEV crew.

Once the range of CEV EIRP options is determined, the question of possible constraints to the relay is examined in the following context.

1. It is assumed that the State 1 support is less than what is required to support manned exploration, either in Mars orbit or on its surface.
2. It is assumed that the State 2 support is significantly greater than what is required when robotic missions only are in the Mars environment.
3. The goal of the analysis is to discover whether there is a fixed number of Earth terminals that can be allocated to the Mars mission that supports the two states efficiently.

7.3.4.1 State 1 CEV-Earth Link Results

The results for transmitting 1 Mbps from the CEV to Earth from 2.67 AU are shown in table 7–8. For an antenna of 1 m and power 100 W, a ground array of thirty-seven 12-m antennas is needed. The mass for the link payload is 13.1 kg, including 8.0 kg for a boom and gimbal. (The antenna mass density was taken as 1 kg/m^2 exclusive of the boom and gimbal.) Note that only a minimal decrease in payload mass would occur if 180 antennas were to support the CEV.

TABLE 7–8.—CEV IN TRANSIT AT MAXIMUM DISTANCE 2.67 AU

Number of 12-m ground antennas	Antenna diameter, m	Output power, W	Mass, kg
180	0.9	25	10.32
90	1	41	11.27
45	1	82	12.62
40	1	92	12.91
37	1	100	13.09
4	1	920	47.71

To strive for a significant reduction in the number of ground antennas would take the CEV out of the level-1 “comfort zone” corresponding to {1 m, 100 W}. If the CEV were to utilize a 920-W RF amplifier, the increase factor of 9.2 in EIRP would result in an array reduction from 37 to 4 elements, but such a link would increase the payload to 47.7 kg and the complexity level to 3.

It should be noted that when the CEV is 0.38 AU from Earth it would have the capability of transmitting 49 Mbps to Earth, given that it carries the equipment for 1 Mbps at 2.67 AU.

7.3.4.2 States 1 and 2 Relay-Earth Link Results

According to table 7–9, an array of 45 antennas can support the relay at the same complexity factor as an array of 180 for data rates of 1 Gbps and 100 Mbps. An array of 180 permits realization of a relay link payload at level-2 complexity, whereas a 45-antenna array leads to level 3. Assuming a total of 45 antennas dedicated to the relay during State 2 operations, 37 of these are needed for the CEV (see sec. 7.4.1), leaving eight antennas to support the relay while there is an in-transit, Mars mission CEV. For a relay peak data rate design of 1 Gbps, this allocation permits 180 Mbps to be transmitted to Earth by the relay at the same time the CEV is transmitting 1 Mbps direct-to-Earth at maximum range. For the lower peak rates, 500 and 100 Mbps, the corresponding achievable data rates for the relay reduce to 90 and 18 Mbps, respectively.

TABLE 7–9.—RELAY PERFORMANCE FOR CEV IN TRANSIT (STATE 1) AND IN MARS ORBIT (STATE 2)

State	# 12m Ground Antennas	Data Rate Gbps	Complexity Level
2	180	1	3
2	90	1	3
2	45	1	3
1	8	0.18	3
2	180	0.5	2
2	90	0.5	3
2	45	0.5	3
1	8	0.09	3
2	180	0.1	2
2	90	0.1	2
2	45	0.1	2

7.4 Mars and Beyond

In this section we explore RF capabilities from Mars to beyond Pluto, under the assumption that on the ground there is an antenna array comprising forty-five 12-m antennas. Tables 7–10 and 7–11 summarize the results in terms of antenna size, power, distance, data rate, and complexity factor for a given antenna mass density. There is negligible difference in results between the two cases of antenna mass density.

The results show that a 9-m antenna and 1 kW (moderate to difficult complexity factor) can support on the order of 100 Mbps at Saturn, at least 10 Mbps at Uranus, and better than 1 Mbps at Pluto. Increasing the risk factor to the difficult level and using a {12.8 m, 2.5 kW} transmitter increases the data rate by a factor of 5 beyond Mars. At 2.67 AU (Mars maximum range) this increases the data rate to 2.25 Gbps, and can achieve 4 Gbps at 0.38 AU (Mars closest approach). Both Mars rates are achieved by utilizing bandwidth-efficient coding.

The data rate can increase even more by increasing the antenna size within the level-4 complexity limit; for example, for 18.3 m and 2.5 kW the data rate can be doubled, enabling gigabits to be received from as far away as Saturn.

Although we have entered the yellow risk area (difficult) in these last examples, there is a collective expertise agreement that this can be achieved with the proper investment. The greater concern is related to mass. Tables 7–12 and 7–13 present a summary of results of mass as a function of distance, data rate, and complexity factor for a given antenna mass density. As can be seen, as the EIRP increases, the masses for generating the required EIRP also increase. Thus a 12.3-m antenna and 2.5 kW of RF output have a mass of 334 kg, whereas 652 kg results from a 18.3-m antenna and 2.5 kW (assumed antenna mass density 2 kg/m^2).

Decreasing the mass density can have significant impact. A 50-percent reduction in density leads to a 44-percent mass reduction for the 18.3-m antenna/2.5-kW power pair and a 27-percent reduction for the 12.0-m/2.5-kW pair (table 7–12). Recall that our reference link for 1 Gbps at 2.67 AU is 1 kW and a 9-m antenna. At density 2 kg/m^2 the mass is 186.7 kg, but when reduced to 1 kg/m^2 the mass to 115.6 kg, a 38-percent reduction. Clearly, antenna mass density is a significant factor in determining the practicality of the realization of RF for very high, space-based EIRP.

TABLE 7–10.—RF SYSTEM MASS FOR VARIOUS DATA RATES AS A FUNCTION OF DISTANCE, WITH AN ANTENNA MASS DENSITY OF 2 kg/m^2 AND FORTY-FIVE 12-m ANTENNAS AT THE GROUND

Data Rate	(Mass Density 2 kg/m^2) Distance (AU)				
	0.38	2.67	8.44	26.7	84.4
(Gbps) 4	12.8 m 2.5 kW				
3	9 m 1 kW				
2.5	6.5 m 0.97 kW	18.3 m 2.4 kW			
2.25		12.8 m 2.5 kW			
1	2.6 m 242 W	9 m 1 kW	18.3 m 2.4 kW		
(Mbps) 500	2.6 m 121 W	6.5 m 0.97 kW	12.8 m 2.5 kW		
100	1.6 m 64 W	4.1 m 487 W	9 m 1 kW	18.3 m 2.4 kW	
50		3.4 m 355 W	6.5 m 0.97 kW	12.8 m 2.5 kW	
10		2.3 m 155 W	4.1 m 487 W	9 m 1 kW	18.3 m 2.4 kW
5		1.9 m 114 W	3.4 m 355 W	6.5 m 0.97 kW	12.8 m 2.5 kW
1		1.3 m 48 W	2.3 m 155 W	4.1 m 487 W	9 m 1 kW
	Mars 0.38- 2.67 AU		Jupiter 4-6 AU	Uranus 18-22 AU	Pluto 31-50 AU
			Saturn 8-11 AU		

TABLE 7–11.—RF SYSTEM MASS FOR VARIOUS DATA RATES AS A FUNCTION OF DISTANCE, WITH AN ANTENNA MASS DENSITY OF 1 kg/m^2 AND FORTY-FIVE 12-m ANTENNAS AT THE GROUND

Data Rate	(Mass Density 1 kg/m^2) Distance (AU)				
	0.38	2.67	8.44	26.7	84.4
(Gbps) 4	12.8 m 2.5 kW				
3	9 m 1 kW				
2.5	9.0 m 0.5 kW	18.3 m 2.5 kW			
2.25		12.8 m 2.5 kW			
1	3.4 m 141 W	9 m 1 kW	18.3 m 2.5 kW		
(Mbps) 500	2.6 m 121 W	9.0 m 0.5 kW	12.8 m 2.5 kW		
100	1.8 m 50 W	4.6 m 378 W	9 m 1 kW	18.3 m 2.5 kW	
50		4.1 m 244 W	9.0 m 0.5 kW	12.8 m 2.5 kW	
10		2.7 m 112 W	4.6 m 387 kW	9 m 1 kW	18.3 m 2.5 kW
5		2.3 m 78 W	4.1 m 244 W	4.6 m 387 kW	12.8 m 2.5 kW
1		1.5 m 36 W	2.7 m 112 W	4.1 m 244 W	9 m 1 kW
	Mars 0.38- 2.67 AU		Jupiter 4-6 AU	Uranus 18-22 AU	Pluto 31-50 AU
			Saturn 8-11 AU		

TABLE 7–12.—RF SYSTEM MASS FOR VARIOUS DATA RATES AS A FUNCTION OF DISTANCE, WITH AN ANTENNA MASS DENSITY OF 2 kg/m^2 AND FORTY-FIVE 12-m ANTENNA ARRAY AT THE GROUND

Data Rate	(Mass Density 2kg/m^2) Distance (AU)				
	0.38	2.67	8.44	26.7	84.4
(Gbps)					
4	334.3				
3	186.7				
2.5	116.3	652			
2.25		334.3			
1	20.6	186.7	652		
(Mbps)					
500	15.6	116.3	334.3		
100	7.3	46.6	186.7	652	
50		36.4	116.3	334.3	
10		16.3	46.6	186.7	652
5		11.5	36.4	116.3	334.3
1		5.2	16.3	46.6	116.3
	Mars 0.38-2.67 AU		Jupiter 4-6 AU; Saturn 8-11 AU	Uranus 18-22 AU	Pluto 31-50 AU

TABLE 7–13.—RF SYSTEM MASS FOR VARIOUS DATA RATES AS A FUNCTION OF DISTANCE, WITH AN ANTENNA MASS DENSITY OF 1 kg/m^2

Data Rate	(Mass Density 1kg/m^2) Distance (AU)				
	0.38	2.67	8.44	26.7	84.4
(Gbps)					
4	257.5				
3	115.6				
2.5	90.5	364.3			
2.25		257.5			
1	16.3	115.6	364.3		
(Mbps)					
500	11.5	90.5	257.5		
100	5.1	32.6	115.6	364.3	
50		25.8	90.5	257.5	
10		11.3	32.6	115.6	364.3
5		8.1	25.8	90.5	257.5
1		3.6	11.3	32.6	115.6
	Mars 0.38-2.67 AU		Jupiter 4-6 AU; Saturn 8-11 AU	Uranus 18-22 AU	Pluto 31-50 AU

7.4.1 Conclusions

Based on the results presented the following may be concluded. Achievable RF power is more of a limitation in reducing EIRP technology risk than is antenna size and mass.

1. It is highly desirable to achieve an antenna mass density of 1 kg/m^2.
2. Antenna sizes of 12 m or less should meet all requirements for Mars exploration.
3. There is a trade space in many cases within which increasing the minimum mass slightly leads to a reduction of technical risk.

If data rate requirements for the farthest Mars distance can be relaxed to obtaining this data rate as an average over a mission, then the required EIRP is reduced. This results in a reduced payload mass and cost.

4. The CEV is in transit for months and there is a requirement to support the CEV while en route (State 1) with at least a minimum of 1 Mbps via a direct link to Earth. Once the CEV achieves Mars orbit it can be supported via the Mars relay (up to 1 Gbps capability at 2.67 AU) and is able to transmit to Earth tens of Mbps (State 2). If the CEV is limited to a 1-m antenna and up to 100 W for its link to Earth, then utilization of approximately 45 antennas to support both States 1 and 2 appears to be an efficient way to utilize array resources.
5. At distances beyond Mars, data rates up to 100 Mbps can be achieved at Saturn, at least 10 Mbps at Uranus, and more than 1 Mbps at Pluto using the same resources that enable 1 Gbps at 2.67 AU (Mars max.). Doubling this data rate increases the mass significantly.

7.4.2. Recommendations

The following recommendations for future work and research have resulted from this study.

1. Research into power systems that achieve Ka-band power of up to 500 W at a technology complexity level of 1, is highly desirable.
2. Research into achieving low-mass (mass density of $1\,\text{kg/m}^2$) Ka-band antenna systems up to 14-m in diameter at complexity levels of 2 is highly desirable.

The next phase of this study should encompass the design of the entire relay, which includes the proximity links. Large Earth-Mars antennas may place significant mass burden on the proximity antennas by requiring long booms to avoid blockage. The study would then be able to add cost as a dimension. Thus, the trade space would include the life cycle cost of the Earth array as compared to the life cycle cost of the satellite payload. This would then narrow the EIRP space to those values that are mission cost effective. As before, the needs of the CEV should be factored into the trade space.

7.5 Reference

7–1 Mankins, J.C.: Research & Development Degree of Difficulty (R&D3). NASA Headquarters Office of Space Flight, Advanced Projects Office White Paper, Mar. 10, 1998.